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Lightning injuries

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From the time predating the written word there are descriptions of death and injury caused by lightning strikes. To this day, lightning is a source of awe, curiosity, inspiration, and fear. The brilliance, power, and destructive capacity of lighting have made it the subject for religion, superstition, politics, and, most recently, scientific investigation. As early as 2200 BC the Akkadians depicted a goddess holding sheaves of lighting bolts in each hand with a weather god driving a chariot with lighting bolts created by the flick of his whip [1]. Beginning around 700 BC the Greeks depicted lightning as a tool of warning or favor hurled by Zeus, their god of thunder. The Greeks thought thunderbolts were invented by Minerva, the goddess of wisdom. Because lightning was a manifestation of the gods, any spot that was struck was regarded as sacred. Greek and Roman temples were often erected at these sites, where the gods were worshipped in an attempt to appease them. Aristotle noted that lightning resulted from the ignition of telluric fumes that made up storm clouds. Socrates, much to the chagrin of his fellow Greeks, purported that lightning was not an instrument of Zeus but was instead caused by a vortex of air. In Roman mythology Jupiter used thunderbolts as a tool of vengeance and condemnation, thus those stuck by lighting were denied burial rituals. Roman emperors were known to wear laurel wreaths or sealskin to ward off lightning strikes. Important matters of state were often decided on by observations of lighting and other natural events [1]. For the

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Vikings, lightning was produced by the hammer of Thor the Thunderer as he rode through the heavens on a golden chariot pulled by two enchanted goats with thunder rumbling from the wheels. Thor tossed lightning bolts at his enemies. Thursday is named for him. In the East, early statues of the Buddha show him carrying a thunderbolt with arrows at each end, and in Chinese mythology the goddess of lightning, Tien Mu, used mirrors to direct bolts of lightning. In Africa the Basuto tribe views lightning as the great thunderbird Umpundulo, flashing its wings in the clouds as it descends to Earth. Even today their medicine men go out in storms and bid the lightning to strike far away. The Native American Navajo culture has a story about the hero Twins who used "lightning that strikes straight" and "lightning that strikes crooked" to kill several mythological beasts that were plaguing the Navajo people and in the process created the Grand Canyon [2].

History shows us that as early as 600 BC Thales of Miletus experimented with electricity by rubbing an amber rod with a dried material, noting that it attracted small pieces of feather and straw. Sir William Gilbert of England, court healer to Queen Elizabeth, repeated this experiment successfully. He coined the phenomena *vis electrica* from the Latin word *electrica*, which is derived from the Greek word for the amber, *electron*. The word electricity was first used by the English writer and physician Sir Thomas Browne in 1646. The modern study of electric phenomena is often traced to the publication of Sir William Gilbert's *De Magnete* in London in 1600. Subsequent experiments in Germany, France, and by the Royal Society of London led to the invention of the Leyden jar in 1745, which was the first device that stored electrical energy, an early equivalent to the modern capacitor [2,3].

Benjamin Franklin is generally regarded as the father of electrical science because he was the first to propose that differently charged objects had different amounts of a single kind of electricity, noting that rubbing the objects merely transferred the electric charges from one object to the other. In June 1752 Benjamin Franklin's famous kite experiment proved that lighting was an electric phenomenon and that thunderclouds are electrically charged [3]. He famously constructed a kite and flew it during a storm. When the string became wet enough to conduct, Franklin, who stood under a shed and held the string by a dry silk cord, put his hand near the metal key attached to the string, causing a spark to jump. Electric charge gathered by the kite had flown down the wet string to the key and then jumped across an air gap to flow to the ground through Franklin's body. He also showed that a Leyden jar could be charged by touching it to the key when electric current was flowing down the string [4]. Contrary to modern myth and legend, neither the kite nor Franklin was struck by lightning. Benjamin Franklin also invented the lighting rod and announced its use in 1753 in *Poor Richard's Almanac*. This idea was initially poorly understood. For instance, religious advocates maintained that it would be blasphemy to install such devices on church steeples as they were divinely protected. This same notion led to significant destruction and loss of life because churches were considered to be safe

storage for munitions but were proven by incidence not to be divinely protected from lightning.

The observation of St. Elmo's fire, an aura appearing around the tip of lightning rods and ships' masts during thunderstorms, contributed to confusion about lightning rods. St. Elmo, derived from the Italian Sant Ermo or St. Erasmus (circa 300 BC), was the patron saint of the early Mediterranean sailors. The presence of St. Elmo's fire at the end of a dissipating storm was thought to be evidence that the prayers of the sailors had been answered and that St. Elmo was present to afford protection. Its presence before or at the beginning of a storm was interpreted as a sign of safety in the coming storm. It was thought that lightning rods and ship masts were diffusers of electric charges that could neutralize a storm cloud passing overhead. This belief was based on the century-old observations of corona, or point discharge. In fact, this aura is created by an electron discharge resulting from the strong electromagnetic field induced during a thunderstorm, akin to the modern concept of the streamer. The glow induced on a lighting rod or mast tip is actually ionized air induced by strong electromagnetic fields. This is only a good omen if the lightning rod or mast is appropriately "grounded" to allow for the electrical energy to traverse without damaging other objects or people present.

Little significant progress was made in understanding the properties of lightning until the late nineteenth century, when photography and spectroscopic tools became available for lightning research. Lightning current measurements were made in Germany by Pockels (1897–1900), who analyzed the magnetic field induced by lighting currents to estimate the current values. C.T.R. Wilson won the Nobel Prize for the invention of the cloud chamber by using electric field measurements to estimate the structure of thunderstorm charges involved in lighting discharges. In the early 1950s Stanley Miller and Robert Urey showed that in the presence of the early universe's atmospheric components (methane, ammonia, water vapor, and hydrogen), the addition of an electrical spark to simulate lightning rendered amino acids and hydroxyl acids, the building blocks of the proteins in living things. Carl Sagan later repeated this *primordial soup* experiment with the addition of hydrogen sulfide and ultraviolet light to simulate the effect of sunlight. He created several sugars and nucleic acids.

Myths, superstitions, and misconceptions

As disquieting and alarming as lightning is, it is equally misunderstood and misconceived. One predominant myth is that lightning strikes are invariably fatal. Because reports in the lay press and literature tend to be biased toward the severe or more interesting cases, these data tend to overestimate mortality. According to an American study of case reports in the lightning literature since 1900, lightning strike carries a mortality of 30% and a morbidity of 70% [5]. Slightly different statistical interpretation of the same data yield

a mortality figure of 20% [6,7]. In more recent studies, mortality has been shown to be as low as 5% to 10% [8].

Another common misconception is that a major cause of death is from burns, but only a small percentage of lighting victims actually sustain deep thermal burns. The only immediate cause of death is from cardiac arrest [5]. Persons who are rendered unconscious without cardiopulmonary arrest are highly unlikely to die despite a high prevalence of serious sequelae in this population. The "crispy critter" myth is the belief that the victim struck by lightning bursts into flames or is reduced to a pile of ashes [9]. The fallacy that lighting victims remain charged or "electrified" after being struck is one that even though clearly false leads to unnecessary deaths by delaying vital resuscitation efforts [9].

Another unfortunate mistaken belief is that one is at risk for lightning strike only when there are storm clouds overhead. In fact, the most dangerous time for a fatal strike is the time preceding the storm [9]. Lightning can travel horizontally as far as 10 miles or more in front of a thunderstorm and seem to occur "out of a clear blue sky," or at least when it is still sunny. The faster a storm is traveling and the more violent it is, the more likely a fatal strike will occur. The end of a thunderstorm has been shown to be as dangerous as the beginning. In addition, winter lighting (thunderblizzard), while rare, is usually more dangerous because it tends to be more powerful than summer lightning [10].

Most people believe that occupation of a building during a thunderstorm affords protection from lightning strikes. In fact, a significant number of injuries occur to persons inside their homes or places of work [11,12]. Plumbing fixtures, telephones, and other appliances attached to the outside of the house by metal conductors allow for side flashes [13]. Hard-wired phones are particularly dangerous because they are usually not grounded to the house's electrical system and act as a conduit for electrical current and can lead to death, neurocognitive deficits, or other injuries [14,15]. It is also believed by many that seeking shelter in small sheds, lean-tos, or tents provides safety from lightning strikes, but such small, unsubstantial shelters can actually increase the risk of injury.

The belief that lightning never strikes the same place twice is false. Radio-television antennas, mountaintops, and structures such as the Empire State Building are struck many times per year. If the circumstances that facilitated the initial strike are still present or recur, the risk of lighting is great again.

More dangerous are myths and misconceptions held by health care providers that might adversely affect the care of lightning strike victims. Misconceptions such as "If you're not killed by lighting, you'll be OK," and "If there are no outward signs of lightning injury, the damage can't be serious" [9] can lead to unnecessary, tragic consequences. There is an increasing body of evidence demonstrating a myriad of long-term debilitating consequences such as peripheral neuropathy, chronic pain syndromes, and neuropsychological symptoms caused by nonfatal lightning strikes [14–16].

Many practitioners also contend that lighting injuries should be treated like other high-voltage electrical injuries. While lightning is an electrical phenomenon and is governed by the same laws of physics, its characteristics are unique. Injuries incurred from a lightning discharge are also unique and should be treated accordingly if iatrogenic morbidity and mortality are to be avoided [17,18]. The medical literature is not immune to propagation of false contentions. The tenet that lighting victims who have resuscitation for several hours might still recover successfully is one such literature-based myth stemming from the idea of suspended animation—the concept that lightning is capable of shutting off systemic and cerebral metabolism. This concept is generally credited to Taussig [19] but is actually based upon a case report by Morikawa and Steichen [20]. While this case does report a longer than usual resuscitation (hours), it is not as miraculous as reported in Taussig's paper.

Other myths

Wearing rubber-soled shoes, raincoats, and so forth will protect a person

Air is an excellent insulator, and lighting, if having already overcome this insulating capacity and traversed miles of air, will have overcome any protective effects of rubber-soled shoes and their ilk.

The rubber tires on an automobile are what protect a person in such a vehicle from lighting injury

In reality, the protective effects of a metal-roofed vehicle are caused by the scientific principle of the Faraday cage, allowing the electrical energy to travel outside the metal conductor (the car body) and dissipate through the rainwater to the ground or off the axles or bumper.

Wearing metal around one's head, neck, fingers, or as cleats on shoes will increase the risk or "attract lightning"

There is no evidence to support the notion that small metal objects that do not greatly extend one's height make one more prone to strike. For instance, an umbrella only increases one's risk if it greatly increases one's height. Such objects, however, might increase the risk of thermal injury because of the extreme temperatures that they transiently possess during a lighting strike.

Lightning always hits the highest object

False. Lightning only "sees" objects about 30 to 50 meters from its tip. There is also ample photodocumentation of lightning striking halfway down flagpoles, in narrow mountain gullies, or at the bottom of the space shuttle gantry.

There is no danger of lightning injury unless it is raining

False. While lightning occurs as a result of thunderstorms, it can travel great distances in front of storms and seem to "come out of the clear blue sky"

to strike a person before any rainfall in the area. It is estimated that approximately 10% of lightning strikes where there is no rain falling in the area of the strike.

Lightning can occur without thunder

False. Whenever there is lighting there is thunder, and vice versa; however, the associated thunder might not be appreciated at the scene of the strike because lightning might travel great distances and local geography or architecture might block the sound waves.

Lightning victims can have "internal burns"

Rarely, if ever, do lightning strikes result in deep internal burns such as those suffered with high-voltage electrical injuries. This is not to say that electrical energy does not seep internally and travel through internal structures causing cellular, central nervous system (CNS), and peripheral nervous system (PNS) damage [9].

Epidemiology of injury

The deployment and operation of real-time lightning detection networks allows researchers to know the distribution of cloud-to-ground lightning. On average, more than 20 million cloud-to-ground strikes are detected each year in the United States [21] with as many as 50,000 flashes per hour during summer afternoons [22]. The National Oceanic and Atmospheric Administration (NOAA) and the NOAA's National Climactic Data Center (NCDC) gather and compile all reports of damaging or notable weather-related phenomena from each National Weather Service (NWS) in the United States. *Storm Data* is published by the NCDC based on these data.

From 1959 to 1994, *Storm Data* reported 3529 deaths, 9818 injuries, and 19,814 property damage incidents caused by lightning. Lightning deaths, injuries, and damages are generally thought to be underreported [23–26] because *Storm Data* relies on newspaper clipping services and the lay press for reporting of lightning events and because lightning-related casualties and lightning-related damages are dispersed in space and time more than other weather-related incidents. In the United States there was an average of approximately 200 deaths per year reported in the 34-year period between 1940 and 1974 [27]. Approximately 100 deaths per year attributed to lighting were reported in a 17-year study ending in 1986 [28]. It is currently estimated that lighting causes 50 to 300 deaths per year in the United States [27] with four to five times as many victims suffering nonlethal injuries [27,28]. Taking these factors into consideration, the NWS currently cites an average of 73 documented cases of lightning-related deaths per year with a speculated actual mean of 100 deaths per year caused by lightning [29]. Lightning was

second only to flash floods and floods in weather-related deaths during the 30-year record compiled in *Storm Data,* ahead of earthquakes, tornadoes, and temperature-related deaths.

Central Florida is consistently the leader in lightning flashes per area in a given year, with some areas in Florida averaging about 12 strikes per square kilometer per year. Flash density decreases to the north and west from there (Fig. 1). Populous eastern states account for many of the other casualties caused by lighting strike (Fig. 2), but when population is taken into account the maximum rate of lightning casualties shifts to the Rocky Mountain and plains states. Wyoming and New Mexico boast the top two population-controlled casualty rates. The only states in the top ten for both casualty and casualty rate are Florida, Colorado, and North Carolina [30].

Storm Data also published that approximately two thirds of flashes occur in the summer months of June, July, and August (Fig. 3); however, in the southeastern states lighting is common year round. Lightning is most common in the afternoon; more than half of all lightning occurs between 15:00 and 18:00 local standard time, whereas the early morning hours between 00:00 and 06:00 account for only a small fraction of strikes (Fig. 4), which is intuitive because the elements for lightning creation (low- and midlevel atmospheric moisture, vertical updrafts, and midday heat) are frequently present along tropical coastlines and in mountainous geography. Investigation of lightning strikes around the world also demonstrates that the predominance of strikes is in summer months in midafternoon in moist atmospheric tropical and mountainous environments [31]. *Storm Data* also reveals that 84% of lightning victims in the 35-year period observed were men and that 91% of the time there was only one victim.

Physics of lightning

The study of lightning discharge and formation is highly complex and involves an entire branch of physics and meteorology; therefore, only the simplest, most common case of thundercloud formation and lightning strike is discussed here. Thunderstorms are created by vertical updrafts, and vertical updrafts are assisted by the presence of cold fronts, mountainous geography, sea and lake breezes, and afternoon heating of warm, moist air (Fig. 5). As warm air rises there is a complex redistribution of charges within the cloud caused by the updrafts and downdrafts created by rising moist air and falling ice particles. Charges are created within the cloud and charge separation continues until the characteristic anvil-shaped thundercloud is formed. Most commonly, the bottom part of a thundercloud becomes negative compared with the ground. The earth, which is normally negatively charged, acquires a positive charge as thunderclouds roll overhead. This induced positive charge tends to flow up to the tips of tall trees, buildings, or people. When the separation of charge and the induced current becomes strong enough, the energy difference might be dissipated as a lightning strike.

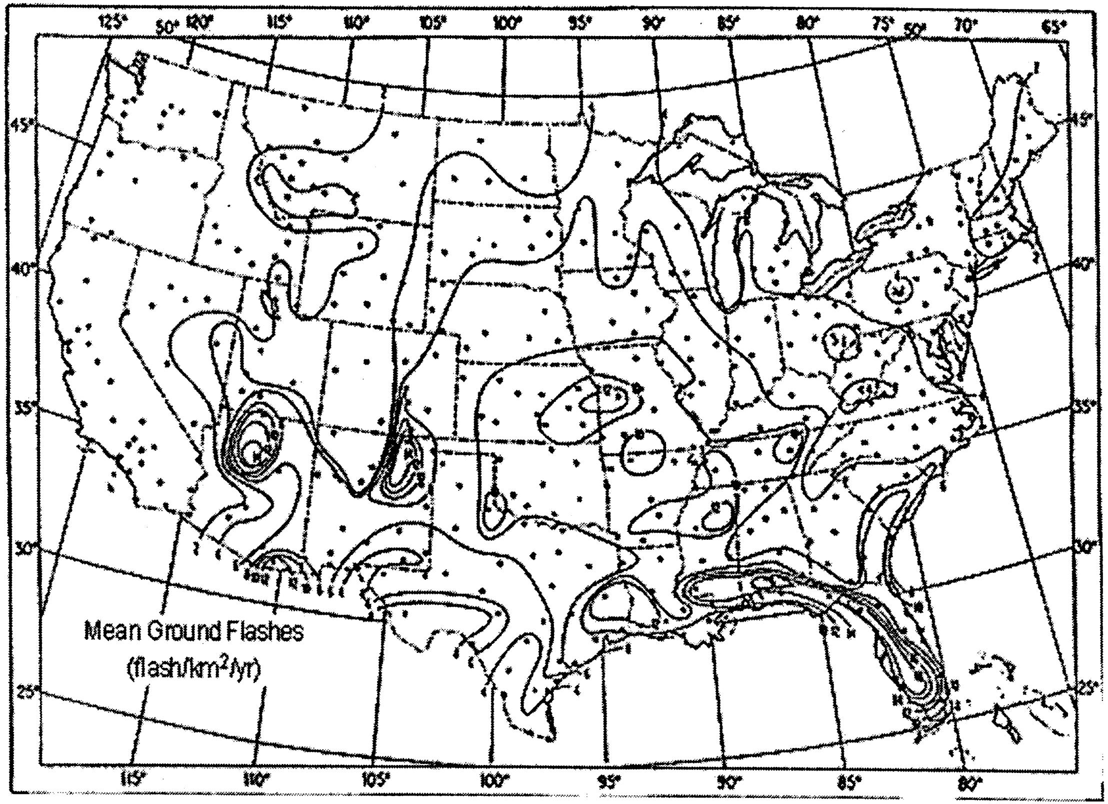

Fig. 1. Lightning strike regions in the continental United States: average United States flash density on the ground. *From* The National Lightning Safety Institute. United States flash density per year, section 6.17.7. Available at: http://www.lightningsafety.com, Accessed September 30, 2003; with permission.

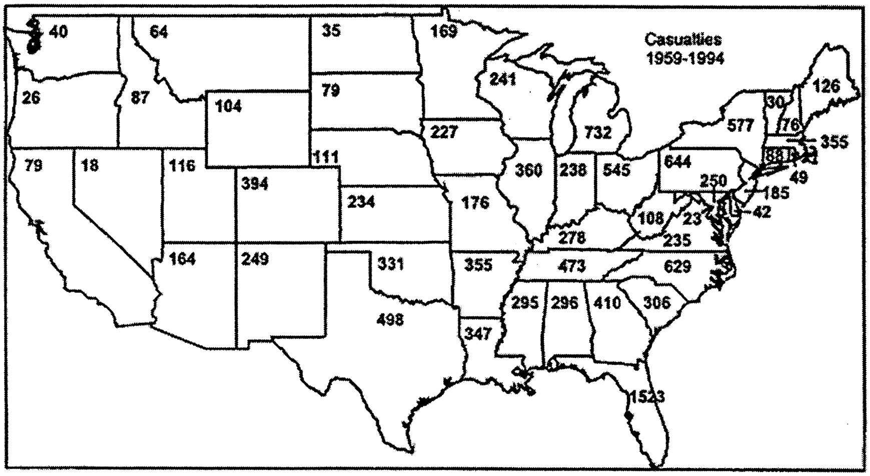

Fig. 2. United States map of lightning casualties by state from 1959 to 1994. *From* Curran EB, Holle RL, Lopez RE. Lightning fatalities, injuries, and damage reports in the United States from 1959–1994. NOAA Tech Memo NWS SW-193, 1997; with permission.

Lightning begins as a relatively weak and slow downward leader from the cloud. The leader breaks down the air and ionizes a path of superheated ions, creating a low-resistance plasma column. The leader steps at approximately 50 meters (164 feet), retreats upward and downward again down the original ionized path, then goes down another 50 meters, and so forth. This polybranching process continues until the leader comes to within 30 to 50 meters (98–164 feet) of the ground. It is worth noting that lightning only "sees" objects within 30 to 50 meters of its tip's radius, thus the tall tree, hill,

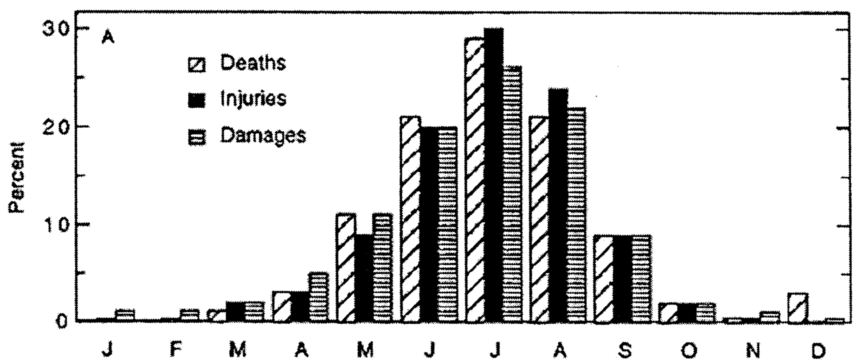

Fig. 3. Monthly variations of lightning fatalities, injuries, and damage reports in the United States from 1959 to 1994. *From* Curran EB, Holle RL, Lopez RE. Lightning fatalities, injuries, and damage reports in the United States from 1959–1994. NOAA Tech Memo NWS SW-193, 1997; with permission.

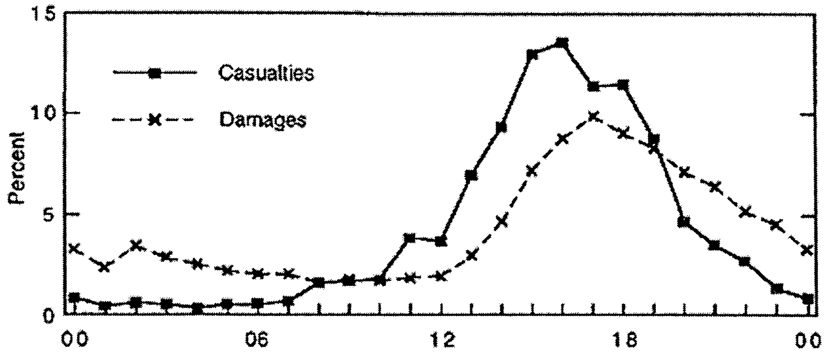

Fig. 4. Time of day of lightning casualty and damage reports for the United States from 1959 to 1994. *From* Curran EB, Holle RL, Lopez RE. Lightning fatalities, injuries, and damage reports in the United States from 1959–1994. NOAA Tech Memo NWS SW-193, 1997; with permission.

or tower 61 meters (200 feet) away are not "seen" by the leader as potential sites for connection. Objects nearest the leader's tip emit upward streamers in response to the induced charge at their tip. When an upward streamer comes into contact with a leader, *attachment* occurs and thus completes a low-resistance plasma channel between earth and ground. As the low-resistance channel is formed by attachment, the potential difference between cloud and ground effectively disappears and the energy available is dissipated in an avalanche of charge between cloud and ground. This avalanche is referred to as the *return stroke,* which is highly luminous. The energy is actually dissipated in the opposite direction (ground to cloud) by way of return strokes [1,10,31].

Lightning occurs in many forms, the most common being streak lightning (Fig. 6). Sheet lightning is a shapeless flash of light that represents lightning discharges within and between clouds. Ribbon lightning is sheet lightning that has been driven by the strong winds of a thunderstorm. Bead lightning occurs when different areas of ionization and charge persist, lending a beadlike appearance to the afterstrokes. Ball lightning is the most unusual, least predictable, and least understood type of lightning. It is usually described as a softball-sized orange to white globe that can enter ships, planes, or houses and travel about injuring people and objects in encounters then exiting by way of a chimney or window, exploding with a large bang, and demonstrating other odd behavior [17,32].

Lightning can be positive or negative, but negative lightning is more common. Positive lightning tends to occur during the winter, during tornadoes, or during violent thunderstorms. It tends to be more powerful than negative lighting and might have a different injury profile.

Thunder is caused by the explosive shockwaves resulting from the instantaneous superheating of the ionized air along the path of a lighting

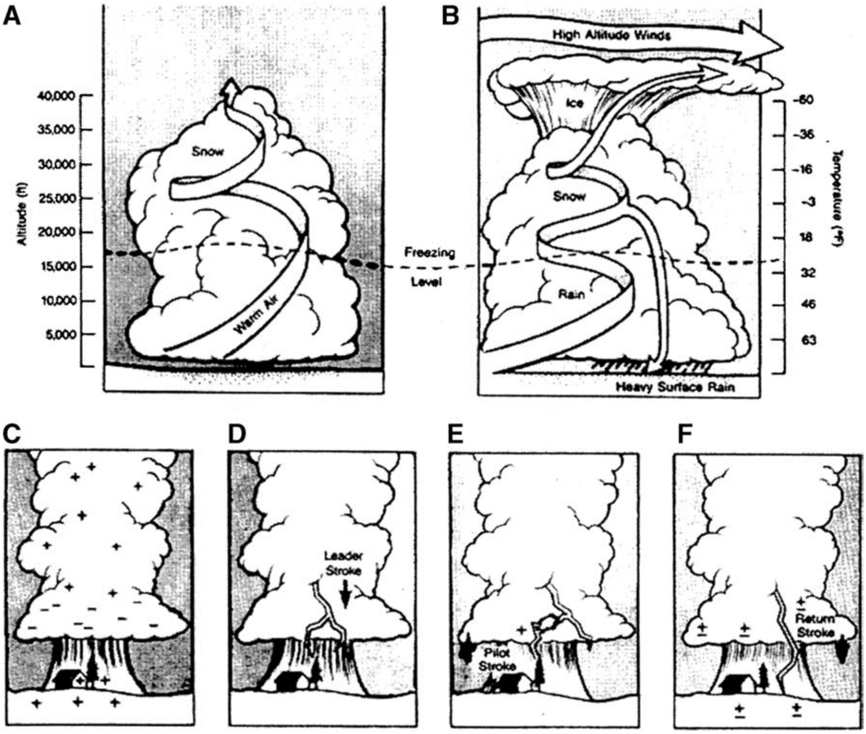

Fig. 5. Process of storm cloud formation and cloud-to-ground lightning discharge. (*A*) Warm, low pressure air rises and condenses into a cumulonimbus cloud. (*B*) Typical anvil-shaped thundercloud. (*C*) Water droplets within the cloud accumulate and layer charges. (*D*) Relatively weak and slow-stepped downward leader initiates the lightning strike. (*E*) Positive upward streamer rises from the ground to meet the stepped leader. (*F*) Return stroke rushes from ground to cloud. Adapted from Copper MA, Andrews CJ, Holle RJ, et al. Lightning injuries. In: Auerbach PS, editor. Wilderness medicine. 4th edition. St. Louis (MO): Mosby; 2001. p. 86; with permission.

stroke [1,31]. The following are a few important accepted principles about thunder [33]:

- Thunder is seldom heard over distances greater than 10 miles (16 km).
- The time interval between the perception of lightning and the first sound of thunder can be used to estimate distance from the lightning stroke.
- Atmospheric turbulence reduces the audibility of thunder.

The thunderclap from a nearby lighting flash is heard as a sharp crack. Distant thunder rumbles as the sound waves are refracted and modified by the storm's turbulence [31]. One can use the difference between the speed of light and the speed of sound to estimate the distance from a given lightning stroke. By counting the number of seconds between the perception of the visual flash and the audible thunder and dividing this number of seconds by five, one can estimate the distance to the strike. This is the "flash-to-bang" method [34].

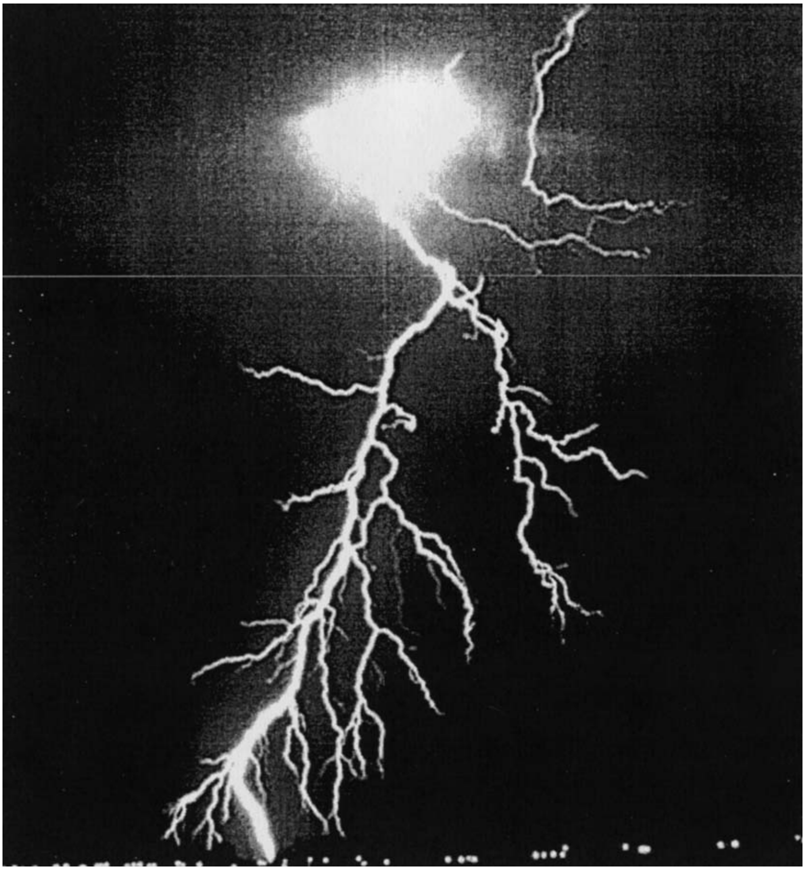

Fig. 6. Typical streak lightning. *From* NOAA Film Library. C. Clark, photographer; with permission.

Mechanism of lightning injury

Lightning can harm objects or humans it encounters by its electrical effects, the heat it produces, and the concussive forces it creates (Box 1). Lightning can also injure indirectly by starting house or forest fires, by felling objects, or by explosive forces. Lightning starts approximately 75,000 forest fires each year and accounts for 40% of all forms of fire. Direct injuries caused by lightning might be caused by a direct hit, splash, contact, step voltage, blunt trauma, or by upward streamers [7,17,35–37].

A direct strike is most likely to hit a person in the open who has been unable to find shelter in a safe location.

Splash injuries occur when lighting that has hit a tree, building, or object splashes onto a victim who might have found shelter nearby [38]. The current seeks the path of least resistance and can jump from the primary strike object,

Box 1. Mechanism of lightning injury

Direct strike
Orifice entry
Contact
Side flash, "splash"
Ground current or step voltage
Blunt trauma

be it a tree or a metal shed, and can splash over to an object or person nearby if they impose less resistance. Splashes can occur from person to person, tree to person, or even indoors from plumbing or telephone wires to people [11].

Contact injury occurs when a victim is in direct contact with an object that is struck or splashed by lightning.

Step voltage, also called stride voltage or ground current, is produced when lighting hits the ground or an object nearby [39]. The current spreads outward radially, diminishing as the radius from the strike increases (proportional to the radius squared). Being primarily composed of salt water, humans offer less resistance than the ground. Even a normal human stride allows for a great potential difference between the legs, thus the current often travels up one leg and down the other in the path of least resistance.

Blunt injury caused by human proximity to the concussive force of the shockwave produced by lightning can lead to a victim being thrown up to 10 yards, tympanic membrane rupture, or other contusions or contusive injuries.

Recently, injury has also been ascribed to the upward leader, or streamer. The upward leader need not make contact with the downward leader to cause injury; just being the conduit for a streamer might lead to injury [40].

Pathophysiology of lightning injury

Lightning is unique from other forms of generator-produced high-voltage electricity. One must understand the physical properties of lightning to understand the spectrum of injuries incurred from a lightning strike. The duration of exposure is the single most important factor in understanding the difference between high-voltage injuries and lightning injuries [7].

Lightning is a unidirectional massive current impulse to be clearly differentiated from direct or alternating current. Lightning occurs when the large potential difference between cloud and ground, measured in millions of volts, is broken down. Upon attachment, this potential difference disappears as an enormous current flows impulsively for a short time. Thus, lightning is best thought of as a "current" phenomenon rather than a "voltage" phenomenon [18].

According to Joule's law (energy = current^2 $\times$ resistance $\times$ time), as the resistance goes up, so does the heat generated by the passage of the current. In

humans, when low energy levels are encountered, much of the electrical energy is dissipated by the skin.

It takes a finite amount of time for the skin to break down when exposed to heat or energy. After lightning meets the body current it is initially transmitted internally, after which the skin breaks down and there is an external ‘‘flashover.’’ As current flashes over the outside of the body it can vaporize moisture on the skin and blast apart clothes and shoes, leaving the victim nearly naked. While the current from a lightning strike only flows internally for a short time, it can cause short-circuiting of electrical systems such as the heart, respiratory centers, and autonomic nervous system, as well as spasm of arterioles and muscles [41]. Lightning tends to cause asystole rather than ventricular fibrillation. While cardiac automaticity might reestablish a rhythm, the duration of respiratory arrest can lead to secondary deterioration of the rhythm to refractory ventricular fibrillation and asystole [5,42]. This secondary arrest has been shown experimentally in sheep [43]. Lightning rarely flows internally long enough to cause significant burns or tissue destruction. Deep tissue burns and myoglobinuric renal failure are not common injury patterns in lightning strikes. Other injuries caused by blunt trauma or ischemia from vascular spasms, such as myocardial infract or spinal artery syndromes, can also occur [17,44–47].

Injuries from lightning

Lightning is an instantaneous, unpredictable phenomenon with a myriad of physical characteristics ranging from trivial to fatal (Table 1). For prognostic purposes, victims can generally be considered as being in one of three groups: minor injury, moderate injury, and severe injury [10].

Minor injury

Victims who have minor injury might report dysesthesias in the effected extremity or a feeling of having been hit on the head or having been in an explosion. They might or might not have perceived lightning or thunder. They might also complain of confusion, amnesia, temporary unconsciousness, temporary deafness, or blindness [32]. Victims might also complain of parasthesias, muscle pain, confusion, or amnesia lasting hours to days. Victims might suffer tympanic membrane rupture. Vital signs are usually stable, although some victims experience transient mild hypertension. Permanent neurocognitive damage can occur.

Moderate injury

Victims who have moderate injury might be disoriented, combative, or comatose. Victims frequently demonstrate motor paralysis with mottled skin and diminished or absent pulses, usually of the lower extremities.

Table 1
Lightning injuries by body system

Body system	Injuries
Integumentary system	Linear, punctuate, and partial- or full-thickness burns; keraunographic markings
Cardiac system	Ventricular fibrillation; asystole; hypertension; tachycardia; nonspecific ST segment and T wave changes; prolonged QT intervals; premature ventricular contractions; myocardial infarction
Central nervous system	Weakness; amnesia; confusion; intracranial injuries; immediate loss of consciousness; brief aphasia; paraplegia; quadriplegia; spinal cord damage; cold, mottled, pulseless extremities
Eyes and ears	Tympanic membrane perforation; secondary otitis media; transient dizziness; temporary or permanent deafness; dilated or nonreactive pupils; transient blindness; corneal edema; uveitis; vitreous hemorrhage; cataracts
Other injuries	Myoglobinuria (rare); myalgias; hypothermia; blunt trauma including skull, vertebral, rib, and extremity fractures

Adapted from Lewis AM. Understanding the principles of lightning injuries. J Emerg Nurs 1997;23(6):535–41; with permission.

Nonpalpable pulses might indicate arterial spasm and sympathetic instability, which must be differentiated from hypotension, which might also be caused by fracture or blunt injury. Spinal shock from cervical or other spinal fractures must also be considered. Moderately injured victims might suffer temporary cardiopulmonary standstill with spontaneous recovery of pulses secondary to return of cardiac automaticity. Seizures can also occur. First- and second-degree burns might be present initially or evolve over the first several hours. Tympanic membrane rupture should be anticipated, whereas hemotympanum should prompt consideration of a basilar skull fracture. While clinical recovery is often rapid within the first few hours, moderately injured victims are prone to suffering long-term sequelae such as sleep disorders, irritability, difficulty with fine psychomotor functions, parasthesias, generalized weakness, sympathetic or nervous system dysfunction, and posttraumatic stress syndrome. Atrophic spinal paralysis, although rare, has been reported.

Severe injury

Victims who have severe injury might be in cardiac arrest with ventricular standstill or fibrillation when first examined. Cardiac resuscitation might be unsuccessful if the victim has suffered prolonged cardiac or CNS ischemia. Tympanic membrane rupture with hemotympanum and cerebral spinal fluid (CSF) otorrhea is common in the severely injured group. Direct brain damage can occur. The prognosis is usually poor in the severely injured patient because of direct lightning damage, often complicated by a delay in initiating cardiopulmonary resuscitation with resultant anoxic injury to the brain and other organ systems [10].

Differences between injuries from high-voltage electricity and lightning

There are marked differences between injuries caused by high-voltage electrical accidents and lightning (Table 2). Lightning contact with the body is nearly instantaneous, often leading to flashover. Exposure to high-voltage generated electricity tends to be more prolonged because the victim often freezes to the circuit. After skin breakdown, the prolonged flow of current in high-voltage accidents tends to cause massive internal thermal injuries, sometimes necessitating major amputations [17]. Myoglobinuric renal failure caused by massive release of myoglobin and compartment syndromes requiring fasciotomy are somewhat common. In contrast, lightning injury rarely leads to deep burns [18].

Cardiopulmonary arrest

The most common cause of death in a lightning victim is cardiopulmonary arrest. A victim is highly unlikely ($P<0.0001$) to die unless cardiopulmonary arrest is suffered as an immediate effect of the strike [5]. In addition to primary cardiac arrests, secondary cardiac arrests have also been reported [6,18,19,43]. Injury first occurs with cardiac arrest and pulmonary standstill. Because of the inherent automaticity of the heart, organized contractions generally resume within a short time. The respiratory arrest caused by paralysis of the medullary respiratory center might last far longer than cardiac arrest. Unless the victim receives immediate ventilatory assistance, hypoxia might induce arrhythmias and secondary cardiac arrest. Bradycardia, tachycardia, premature ventricular contractions, ventricular tachycardia, and atrial fibrillation have also been reported [5].

ECG ST wave changes consistent with ischemia and damage to the subepicardial, posterior, inferior, and anterior territories are somewhat common [44]. While creatinine kinase (CK) myocardial band (MB) isoenzyme elevations have been reported in association with lightning injury,

Table 2
Differences between lightning and high-voltage electricity

Factor	Lightning	High-voltage electricity
Energy level	30 millon volts, 50,000 amps	Usually much lower
Time of exposure	Brief, instantaneous	Prolonged
Pathway	Flashover, orifice	Deep, internal
Burns	Superficial, minor	Deep, major injury
Cardiac	Primary and secondary arrest, asystole	Fibrillation
Renal	Rare myoglobinuria or hemoglobinuria	Myoglobinuric renal failure is common
Fasciotomy	Rarely if ever necessary	Common, early, and extensive
Blunt injury	Explosive thunder effect	Falls, being thrown

Adapted from Copper MA, Andrews CJ, Holle RJ, et al. Lightning injuries. In: Auerbach PS, editor. Wilderness medicine. 4th edition. St. Louis (MO): Mosby; 2001. p. 94; with permission.

the role of troponin levels in evaluating lightning strike victims is not well understood. ECG changes might be delayed for as long as 1 week, rendering the initial screening ECG a poor tool in evaluating ischemia. Areas of focal cardiac necrosis have been demonstrated in autopsies, and histologic changes consistent with myocardial necrosis have been shown in sheep hearts [6]. Most ECG changes resolve within a few days, but some might persist for months [39]. The QT interval might be prolonged following lightning strike [48].

Pulmonary edema, pulmonary contusion with hemoptysis, and pulmonary hemorrhage caused by blunt injury or direct lung damage has also been reported [49].

Neurologic injuries

Nervous system injury far and away causes the greatest number of long-term problems for survivors of a lightning strike. Damage is possible to the central, peripheral, and sympathetic nervous systems. Numerous tools are available for the diagnosis and injury of neurologic injuries in lightning strike victims. Functional scans such as single-photon emission computed tomography (SPECT) are often positive. Anatomic scans such as CT and MRI are usually negative. Electroencephalogram (EEG) is often mentioned in the literature but is of variable utility and might be normal [18]. Neuropsychological assessment and tracking, cognitive retraining, pharmacotherapy, and psychotherapy are other options.

Central nervous system injury

Current traversing through the brain can lead to coagulation of brain substance, formation of epidural and subdural hematomas, respiratory center paralysis, and intraventricular hemorrhage. Head CT might show diffuse edema or intracranial hemorrhage but is more commonly normal [50–52]. Direct brain damage from blunt trauma can occur and should be pursued in any victim whose mental status deteriorates over time [50,51]. Meningeal and parenchymal blood extravasation, petechiae, dural tears, scalp hematomas, and skull fractures have been documented by autopsy findings in lightning strike victims. Because of the flow of current through the CSF and brainstem, cardiopulmonary arrest, sleep disturbances, and endocrine dysfunction can occur. Persistent paresis, paresthesias, incoordination, delayed and acute cerebellar ataxia, hemiplegia, aphasia, and atrophic spinal paralysis have also been reported.

Hypoxia or intracranial injuries can lead to early seizures in lightning strike victims. EEG might demonstrate focal or diffuse epileptogenic foci. These EEG changes usually normalize over the course of months. Children are especially prone to delayed seizures, which present as "absence spells," memory loss, or blackouts. Anoxic brain injury caused by prolonged cardiopulmonary arrest might be present but is not specific to lightning injury.

Lightning victims almost universally demonstrate anterograde amnesia and confusion regardless of whether or not they were rendered unconscious by the strike. These symptoms usually last for hours to days. Retrograde amnesia is far less common. The victim might be unable to assimilate new information and experiences for several days. In addition to sleep disturbances, altered fine psychomotor function, and posttraumatic stress disorder, victims might experience mood abnormalities, dysesthesias, headaches, emotional lability, libido alterations, storm phobias, decreased exercise tolerance, Parkinsonism or extrapyramidal syndromes, centrally derived pain, psychological syndromes, and cerebellar dysfunction and atrophy [53].

Peripheral nervous system injury

Pain and paresthesias are prominent features of peripheral injury, commonly in the line of current passage. Symptoms can be delayed weeks to years. In severely injured lightning victims, nearly two thirds of patients demonstrate some degree of lower extremity paralysis (keraunoparalysis), whereas almost one third demonstrate upper extremity paralysis [5]. The affected extremities appear cold, clammy, mottled, insensate, and pulseless because of sympathetic instability and intense vascular spasm akin to Raynaud's phenomenon, which usually clears after several hours [17,18]. By understanding the mechanism of keraunoparalysis and performing serial examinations, unwarranted fasciotomies can almost always be avoided in the lightning-injured patient; fasciotomy is almost never indicated in the lightning injured patient. There is also evidence of autonomic neuropathy.

Autonomic dystrophy

Autonomic dystrophy, also called sympathetic dystrophy or sympathetically mediated pain syndrome, can occur in a lighting strike victim. The victim might exhibit perfusion alterations, altered temperature control, and altered skin appearance and reactions in affected limbs. These symptoms might later extend to initially unaffected areas. Autonomic dystrophies can have associated pain and movement disorders.

Reflex sympathetic dystrophy, a deep peripheral nerve disorder caused by injury to nerves, is a long-term sequela to damage that is characterized by pain, edema, autonomic dysfunction, and movement disorder. A partial nerve injury causes "causalgia," a burning sensation of a limb along the course of a peripheral nerve, usually with associated skin changes. Causalgia requires some form of intact, albeit damaged, sympathetic function. Movement disorder might be marked, with initiation difficulty, weakness, spasm, and dystonia [10,54–59].

Posttraumatic headache

Many victims of lightning injury exhibit severe, unrelenting headaches for the first several months following lighting injury. Many suffer from nausea

and severe, unexpected, frequent vomiting episodes. Dizziness and tinnitus are also common complaints [60].

Burns

Many people believe that because of the massive discharge of energy encountered in a lightning strike, victims will be "flash cooked" [9,32]. In fact, the flashover saves most victims from incurring anything more than minor burns. If the electric field in a tissue becomes too large, electrons can be freed from their atoms (dielectric breakdown) [41]. Discrete entry and exit points are rare in lightning injury. The burns most commonly seen can be subdivided in to five categories: linear burns, punctate burns, feathering or flowers, thermal burns from ignited clothing of contact with rapidly heated objects, and combinations.

Linear burns are 1 to 4 cm wide and tend to follow areas of heavy sweat concentrations such as beneath the breasts, down the midchest, and in the midaxillary line [17,36]. Linear burns are usually first- and second-degree burns that might be present initially or develop as late as several hours after the lightning strike. These are most likely steam burns secondary to the vaporization of sweat or rainwater caused by the flashover phenomenon on the victim's skin.

Punctate burns appear as multiple, closely spaced, discrete circular burns that individually range from a few millimeters to a centimeter in diameter. They might be full thickness and resemble cigarette burns, but they are usually too small to require grafting.

Feathering burns, also known as Lichtenberg's flowers, keraunographic markings, arborescent burns, and ferning, are pathognomonic of lightning and are not true burns because there is no damage to the skin itself (Fig. 7) [38,61,62]. They appear as transient arborescent marks that follow neither the vascular pattern nor the nerve pathways are usually pink to brownish in color and are sometimes lightly palpable. There are references to these markings in the bible, in which they were described as representing photographic imprints of the victim's surrounding vegetation [10]. The pattern is similar to that induced on a photoelectric plate when it is exposed to a strong electric field. A visual relationship to fractal geometry cannot be ignored. It is thought that they represent red blood cells extravasated into the superficial layers of the skin from capillaries secondary to the dielectric breakdown of the skin and subsequent massive electron shower. No histologic changes have been found to date on skin biopsy in victims rendered with keranographic markings [63]. Experimental animal models suggest that keranographic markings follow the current lines seen in flashover [64].

Thermal burns can occur if the victim's clothing is ignited or if the victim was wearing metal. Necklaces, belt buckles, rings, pocket change, and other such items in the grasp or in contact with a lightning strike victim can lead to

Fig. 7. Feathering burns. *From* Domart Y, Garet E. Lichtenberg figures due to a lightning strike. N Engl J Med 2003;343:1536; with permission.

second- or third-degree burns to the adjacent skin as the objects become heated rapidly by the electric energy [36].

Victims of lighting can exhibit any combination of burns. It has been shown retrospectively that persons who suffer cranial burns are four times more likely to die and two and a half times more likely to

suffer cardiopulmonary arrest than those who do not have cranial burns [5].

Blunt and explosive injuries

Lightning strike victims might be injured directly from the explosive force of lightning, by a fall, or by being thrown by endogenous opisthotonic contractions. Skull, rib, extremity, and spine fractures can occur. Rarely, a burst-like injury of soft tissues occurs and produces extensive deep tissue injury, especially in the feet, where boots or socks can come apart or be blown off [10].

Myoglobinuric renal failure has yet to be reported in a lightning strike victim. Hemoglobinuria and myoglobinuria are seldom reported, but when they do occur they are transient.

Persistent hypotension should alert the physician to underlying blunt injuries to the chest, heart, lungs, spine, and intestines. Pulmonary contusion, heart failure, ischemic bowel, and coma are other rare but noteworthy complications.

Eye injuries

Ocular injuries can be caused by direct thermal or electrical damage, intense light, contusion from the shock wave, or combinations of these factors. More than half of persons struck by lighting will incur ocular injury. Cataracts most commonly develop within the first few days but can occur as late as 2 years after the strike and are frequently bilateral [65]. Corneal lesions, hyphema, uveitis, iridocyclitis, and vitreous hemorrhage occur with greater frequency than do choroidal rupture, chorioretinitis, retinal detachment, macular degeneration, and optic atrophy [66]. Diplopia, loss of accommodation, and decreased color sense have also been reported.

Mydriasis, Horner's syndrome, anisocoria, and loss of light reflexes represent autonomic disturbances of the eye and can be transient or permanent. Transient bilateral blindness of unknown etiology is somewhat common. The victim might have intense photophobia [66].

Dilated or unreactive pupils should never be used as a prognostic sign or criterion for brain death in lightning victims until all anatomic and functional lesions have been ruled out [67].

Ear injuries

Temporary deafness is somewhat common. Sensorineural hearing loss might be caused by the intense noise and shock wave accompanying thunder and the passage of current into cranial orifices. Approximately 50% of lightning victims have rupture of one or both tympanic membranes [11]. CSF otorrhea and hemotympanum can occur and should prompt exoneration of basilar skull fracture by CT examination of the head. Ossicle disruption,

permanent deafness, facial palsies, nystagmus, vertigo, tinnitus, and ataxia can follow otologic damage [68].

Fetal survival

The prognosis of the fetus of a pregnant woman struck by lightning is unpredictable [5]. Of 11 reported cases, five of the pregnancies ended in full-term live births without recognizable abnormality in the child, three resulted in live births with subsequent neonatal death, and the remainder were stillbirths or deaths in utero.

Hematologic abnormalities

Several unusual hematologic abnormalities have been attributed to lightning injuries. Examples include disseminated intravascular coagulation, transiently positive Coomb's test, and Di Guglielmo's syndrome, which is characterized by erythroblastosis, thrombocytopenia, and hepatosplenomegaly [10].

Endocrine and sexual dysfunction

Lightning strike victims have reported menstrual irregularities lasting 1 to 2 years. Amenorrhea and premature menopause have also been reported. Impotence and decreased libido are common complaints. There is one unsubstantiated report of male hypersexuality subsequent to lightning strike [10].

Psychological dysfunction

It is somewhat common for the minimally to moderately injured lightning victim to delay presentation to medical care practitioners until symptoms do not abate or family members insist. Neurocognitive deficits might not become apparent until a victim attempts skilled mental functions. Victims are often unable to continue their prestrike occupation because of decreased work tolerance, short-term memory problems, and difficulty assimilating new information. As medical practitioners it is imperative to not brashly discount complaints as malingering, excessive reaction, conversion reaction, personality problems, or manifestations of "weak" coping strategies [10].

The postlighting strike syndrome has multiple important components: functional issues, behavioral issues, and depression. Individuals often show marked diminution of short-term memory ability, are unable to focus attention for more than a short period of time, and suffer diminished mental agility. They are neither able to coordinate multiple tasks simultaneously nor to follow orders for complex tasks that they used to perform easily before the injury. Individuals also often find that they are more aggressive than before

the injury was incurred. Extreme fatigue, sleep disturbance, or hypersomnolence that might last for years are common. Flashbacks and nightmares might be experienced. Avoidance of the precipitant circumstance might be demonstrated, often in extreme proportion consistent with posttraumatic stress disorder. Depression is almost always present and should be anticipated. The depression can be in reaction to the decrements in work power and lifestyle engendered by chronic pain or decreased personal performance. There might also be depression as a primary organic entity or as a combination of reactive and organic etiologies. Antidepressant medication is useful. The first 12 months after injury are crucial to recovery; it is in this period that most recovery is seen, with possible mild improvement seen for up to 3 years after injury. Beyond this time chronic dysfunction can be assumed.

Recognition and treatment of lightning injuries

Diagnosis

The diagnosis of lightning injury might be difficult. A history of a thunderstorm, eyewitness reports, and typical physical findings in the victim make diagnosis easier.

The diagnosis might be easily confused with other entities (Box 2), especially when a victim is struck while alone in a field or when the blunt trauma incurred in the presence of disarray of clothing and belongings raises the suspicion of assault. It is important to remember that lighting can strike on a relatively clear day or night and that the sound of thunder might not always be appreciated. A diligent historical effort and a careful physical examination at the earliest possible opportunity are imperative to prompt diagnosis. A person who has linear burns and exploded clothing should be treated as a lightning victim. Feathering marks are pathognomonic of lightning strikes and occur in no other type of injury, but burns of any type are not always present. Tympanic membrane rupture, confusion, outdoor location, and lightning-associated burns are important clues. Lightning strike should be considered in persons found confused or unconscious indoors after or during a thunderstorm because side flashes from indoor plumbing and telephones can occur.

Initial first aid and triage of victims

The first priority in any rescue is scene safety. No rescue attempt should be made if it puts the health or lives of the rescuers in danger. When entering a rescue scene, consideration should be made regarding the resources available, the time, and the method of delivery to definitive medical care.

In lightning, as in other emergencies, the first steps are the ABCDE's of resuscitation: airway, breathing, circulation, disability, and environment/exposure. This should be followed by a careful history and a careful

Box 2. Differential diagnosis of lightning injury

- Cerebrovascular accident
  - Subarachnoid hemorrhage
  - Intraventricular hemorrhage
  - Stroke
- Seizure disorder
- Spinal cord injury
- Closed head injury
- Hypertensive encephalopathy
- Cardiac arrhythmia
- Myocardial infarction
- Toxic ingestion
- Malingering, conversion reaction

Adapted from Copper MA, Andrews CJ, Holle RJ, et al. Lightning injuries. In: Auerbach PS, editor. Wilderness medicine. 4th edition. St. Louis (MO): Mosby; 2001. p. 102.

head-to-toe secondary examination. If the victim is in cardiac arrest, cardiopulmonary resuscitation (CPR) should be started immediately and a rescue vehicle called for transportation, preferably by activating 911. If the strike occurs far from civilization and evacuation is improbable, the victim will probably die unless pulse and respirations resume in a short period of time. The heart might resume activity but then slip into secondary cardiac arrest. If the rescuer is successful in obtaining a pulse with CPR, ventilation should be continued until spontaneous adequate respirations resume, the victim is pronounced dead, continued resuscitation is deemed unfeasible owing to rescuers' exhaustion, or there is danger to the rescuers' survival.

When lighting strikes involve multiple victims, resources and rescuers might not meet the demand and triage must be instituted. The normal rules of triage in multiple-casualty situations dictate bypassing the dead for those who are moderately or severely injured and can benefit from resuscitation efforts; however, "reverse triage" or "resuscitation of the dead" is the rule in lighting incidents because victims who show some return of consciousness or who have spontaneous breathing are already on the way to recovery. In the field, the most vigorous attempts at CPR should be directed to the victims who appear to be dead because they might ultimately recover if properly resuscitated. Survivors should be routinely stabilized and transported to the hospital for more thorough evaluation. All victims of lightning strike, no matter how minor the injury might appear, should be evaluated in an emergency department.

Other than a few anecdotal reports, there is no reason to believe that lightning victims can recover after prolonged CPR. If the victim has not

regained a pulse after 20 to 30 minutes of resuscitation, as in most cardiac arrests, the chances for recovery are slim to none and the rescuer should not feel guilty about stopping the resuscitation. Before pronouncing the victim dead, the rescuer must be sure that other reversible problems such as hypothermia are not clouding the victim's response to resuscitation efforts.

Whenever indicated and feasible, other stabilization procedures such as splinting of fractures, endotrachial intubation, spinal immobilization, and the institution of intravenous fluids and oxygen should be accomplished [10,17,36].

History and physical examination

As with any patient, primary assessment and stabilization of the ABC's, history, and complete secondary surveys are the rule. Because victims are often confused and amnestic, eyewitness reports and prehospital provider observations are helpful. The history should include the description of the event and the victim's behavior following the strike.

Complete exposure of the patient is imperative. After completely exposing the patient, the vital signs, including core temperature and level of consciousness, must be measured and recorded. Because many lightning victims are struck during a storm, they should be assumed to be wet and cold. All wet contacts should be removed and hypothermia should be anticipated and treated accordingly. The awake patient should be assessed for orientation and short-term memory. While victims might be able to carry on a social conversation, they might often have underlying deficits in the assimilation of information and other fine neurocognitive skills. Perseveration and confusion are common. As in most mechanisms of injury, continuing confusion or deterioration of the victim's level of consciousness mandate CT of the head to rule out intracranial injury.

Careful examination of the victim's eyes to establish pupillary reactivity, visual acuity, and ocular injury must be performed. Tympanic membrane rupture should be expected and treated accordingly. Ossicular disruption might explain a victim's lack of appropriate response to verbal stimuli.

The cardiovascular examination should include distal pulses and capillary refill in all extremities, appreciation of arrhythmias, and evaluation of cardiac damage, including isoenzymatic and ECG changes. Pulmonary edema and adult respiratory distress syndrome, if present, are usually late findings.

The victim's abdominal examination might occasionally demonstrate absent bowel sounds, suggesting ileus or acute traumatic injury such as spleen, liver, or bowel contusion.

The entirety of the victim's skin should be evaluated. Burns are not universally present and might take hours to evolve. The skin might show mottling, especially below the waist. Notation of color, pulses, movement, and sensory examination of the victim's extremities are important.

The physical findings and mental state of minimally and moderately injured patients tend to change considerably over the first few hours and should be followed, documented, and treated accordingly. The minimally injured patient can usually be discharged to the care of a responsible person or might require only overnight observation for serial mental status examinations, whereas the moderately or severely injured victim might require intensive care with mechanical ventilation, antiarrhythmic medications, and invasive interventions and monitoring techniques as appropriate to their injuries.

Laboratory tests and radiographs

Minimum laboratory examinations include a complete blood cell count and urinalysis, including a test for myoglobin on fresh urine. The severely injured patient warrants an electrolyte screen, blood urea nitrogen, and creatinine. Serial cardiac enzymes, isoenzyme tests, and troponin might be indicated. Arterial blood gases are necessary for ventilated patients. Serum osmolality might be required if intracranial pressure monitoring is used.

An ECG is essential in all lightning patients and might show QT prolongation, even when otherwise normal.

Radiographs and other imaging studies might be needed depending on the clinical scenario and history. Cervical spine imaging should be obtained if there is evidence of cranial burns, contusions, loss of consciousness, or a change in mentation that precludes a reliable physical examination, or if there are other mechanistic considerations like having been thrown or a fall. The unconscious, confused, or deteriorating patient requires a CT or MRI of the brain to identify trauma or ischemic injury. Radiographic studies to rule out fractures, dislocations, and other bony injuries should be ordered as indicated.

Treatment

Fluid therapy

Any victim who has unstable vital signs, unconsciousness, or disorientation warrants large bore intravenous access. If the victim is hypotensive, fluid resuscitation with normal saline or Ringer's lactate solution should be instituted cautiously, remembering that significant cerebral edema can develop. Fluid restriction in normotensive or hypertensive lightning strike patients might be required because of the risk of cerebral edema.

Moderately and severely injured victims might warrant arterial or central venous pressure monitoring. An indwelling urinary catheter might be needed to carefully measure the intake and output. Because myoglobinuria is rare and usually transient, mannitol diuresis, alkalinization, and aggressive fluid loading are rarely necessary.

Fasciotomy

The presence of keraunoparalysis, paralyzed and pulseless extremities seen with lightning injuries, should *not* be treated like similar-appearing traumatized extremities caused by high-voltage electric injuries. The victim's extremity should be treated expectantly [17,36,69]. Steady improvement in the mottled, cool extremity with return of pulses in a few hours is the rule rather than the exception. Fasciotomy should only be considered if the affected extremity shows no signs of recovery over time and elevated intracompartmental tissue pressures are documented.

Antibiotics and tetanus prophylaxis

Unless a victim has incurred an open fracture, a depressed cranial fracture which violates the dura, or an extensive, dirty wound, antibiotic prophylaxis is not warranted. Standard therapy should follow culture and identification of pathogens. Appropriate tetanus prophylaxis is mandatory if burns or lacerations are present.

Cardiovascular therapy

The management of cardiac arrest is standard. In the victim who is not in cardiac arrest, vasospasm might make it difficult or impossible to palpate or record blood pressure and might require Doppler examination. The femoral and carotid pulses are usually still appreciable, given the patient is not in cardiac arrest.

If a victim is truly hypotensive, fluid resuscitation should be initiated to establish adequate blood pressure and tissue perfusion. True hypotension mandates a search for other causes of shock such as major fractures, blood loss from abdominal or chest injuries, spinal shock, cardiogenic shock, and the rare instance of lightning-associated deep thermal burns. Lightning strike alone rarely, if ever, causes hypotension. Blood products should be administered as indicated. When an adequate blood pressure has been attained, the practitioner should attempt to restrict fluids as tolerated because of the high incidence of cranial injuries and cerebral edema.

All lightning strike victims should have an ECG. Complaints of chest pain, ECG evidence of ischemia, or arrhythmia warrants cardiac monitoring, serial isoenzymes, and troponin levels. The indications for antiarrhythmic drugs and pressor agents are the same as for a suspected myocardial infarction and other critical states [36].

Transient hypertension is usually short-lived and requires no acute therapy unless there is evidence of end-organ damage. In instances of persistent significant hypertension 12 to 72 hours after lightning strike, standard antihypertensive therapy might be warranted.

Respiratory therapy

The victim who is without spontaneous or adequate respirations should be mechanically ventilated until brain death is declared, adequate ventilation resumes, or the physician or family decides to cease efforts. Supplemental oxygen therapy should be administered per the usual indications.

Central nervous system injury

A complete neurologic examination should be performed on every lightning victim. Hospital admission is necessary for patients who demonstrate confusion, demonstrate a focal neurologic deficit, or who have suffered a loss of consciousness. Victims who have tympanic membrane rupture, cranial burns, loss of consciousness, or deteriorating mental status should undergo cervical spine imaging, brain CT, and possibly brain MRI. Serial CT scans might be warranted to follow ventricular hemorrhage or edema.

Intracranial pressure monitoring might be useful in patients who have elevated intracranial pressure [70]. Cerebral edema should be managed in the usual fashion with mannitol, furosemide, fluid restriction, and other standard therapies.

Early seizures are most likely caused by anoxia. If seizures persist after restoration of oxygenation and perfusion or if there is evidence of CNS damage, standard pharmacologic intervention with phenytoin, benzodiazepines, or phenobarbitol should be strongly considered.

If paralysis is present and does not improve with time, other etiologies such as spinal cord injury, spinal shock, or peripheral nerve injury should be investigated. Spinal artery syndrome, characterized by variable loss of motor function, pain, and temperature sensation with sparing of proprioception, has also been rarely reported. These patients need early institution of physical therapy programs. Persistent peripheral neuropathies with dysethesias and weakness might respond to nonsteroidal anti-inflammatory drugs, carbamazepine, and tricyclic antidepressants.

Victims suffering from heightened anxiety, hyperirritability, memory deficits, aphasia, sleep disturbance, posttraumatic stress disorder, personality change, and other forms of brain damage should receive early injury-appropriate referral and rehabilitation. Depression, substance abuse, and suicidality are common late findings and should be addressed. Referral to support groups and other informational sources can be of substantial benefit to victims and their families.

Burns

Lightning burns might be apparent on admission or might develop over the first few hours. They are generally superficial, unlike high-voltage

electrical burns, and seldom cause massive tissue destruction. Aggressive fluid therapy and mannitol diuresis is not indicated. Although rarely seen, the urine should be tested for myoglobin. In the setting of grossly elevated creatinine phoshokinase and myoglobinuria, vigorous hydration, mannitol and alkalinization of the urine can be considered; however, overhydration with resultant cerebral edema has probably killed more lightning strike victims than has myoglobinuric renal failure [10].

Lightning burns are generally so superficial that they do not require treatment with topical agents. In the unusual instance of deep injury, topical therapy should be instituted [69].

Eye injuries

Visual acuity should be measured and the victim's eyes thoroughly examined. Cataracts are common and might be present on initial examination. Eye injuries should be treated in the standard fashion and might require ophthalmologic referral. All patients who are discharged must be given meticulous discharge instructions to seek opthalmologic care at the first instance of visual difficulty or ocular pain [65].

Ear injuries

Simple tympanic membrane rupture can be treated conservatively with observation until the victim's tissues heal. Sensorineural damage to the auditory nerve and facial palsies are somewhat common, and loss of hearing mandates otolaryngology evaluation. Ossicular disruption or more severe damage might require surgical repair. Otorrhea and hemotympanum suggest basilar skull fracture. Occult fractures of the styloid process should be investigated when patients complain of pain around the angle of the jaw [20]. Mora-Magana et al [71] provide a useful review of the otic effects of lightning.

Pregnant victims

If a pregnant woman is struck, fetal viability must be assessed, including fetal heart tones and ultrasound to observe fetal activity. Fetal death is treated with evacuation of the uterus. Demise is treated in the standard fashion.

Other considerations

Gastric irritation is sometimes described. Histamine-2 antagonists or antacid therapy might be indicated. Hemetemeis and ileus might warrant the placement of a nasogastric tube.

Endocrine dysfunction, perhaps as a result of pituitary or hypothalamic damage, including amenorrhea, impotence, and decreased libido, has occurred in some victims.

Pronouncing the victim dead

The question of when to declare a lightning victim dead has always been a matter of some controversy. Dilated pupils should not be taken as a sign of brain death in the lighting victim. It is always necessary to exclude other causes of dysfunction and eliminate them before death is declared [72]. Normothermia should be attained, if possible, before declaring a victim dead. Again, despite anecdotal reports there is no reason to assume nor evidence to suggest that lightning strike victims might benefit from prolonged CPR [67].

Precautions for avoiding lightning injury

Because lightning discharges are so common and most lightning accidents are isolated events, it is impractical for the NWS to warn of every potentially dangerous lighting event. The key to safety is individual education and responsibility.

The exceptions to this rule are when adults are in charge of groups of children and for large, planned events. In the former situation the adult must assume responsibility for the children and have a plan for evacuation. A simple motto to teach children is "If you *see* it, *flee* it; if you *hear* it, *clear* it."

Promoters of large events carry the responsibility for being aware of threatening weather, determining when events should be cancelled or postponed, and having a plan of action that includes proper warning, shelter guidelines and options, and all-clear signals.

Before undertaking excursions or working in the open, everyone should be aware of weather predictions and conditions. Those who cannot avoid working or being outdoors should carry a small radio to monitor weather reports. Be prepared to seek a safe location if a severe thunderstorm watch or warning is announced. If bad weather is expected, someone should appoint a spotter whose duty it is to watch the weather and provide appropriate warning.

The "30-30 rule" states that when the time between seeing lightning and hearing thunder is 30 seconds or shorter, persons are in danger and should be seeking shelter. Outdoor activities should not be resumed for 30 minutes after the last lightning is seen or the last thunder is heard. Because lightning can strike where there is no rain, people should not delay evacuation just because there is no rainfall.

If a storm develops, seek shelter in a substantial building or in an all-metal vehicle. Avoid convertibles or soft-top jeeps. Small buildings such as golf shelters, bus shelters, or rain shelters might actually increase the person's risk, depending on the size and height of the building, because side flashes can occur. Tents offer little to no protection and might actually be worse than no shelter at all because the metal support poles can act as lightning rods. Occupants of tents should stay far away from the poles and any wet garments

as possible. Ground pads seem to afford increased protection against ground potential but are not foolproof.

In the setting of outdoor events such as sports, a series of school buses or minivans can provide safety to attendants and participants. Access to large public buildings in proximity to the event is useful. If a safe location is not available and a group of people is exposed, they should spread out and stay several yards apart so that in the event of a strike the fewest number are seriously injured by the ground current and by side flashes between persons.

In the event that the above guidelines were not or cannot be followed and one or many are deemed at risk for lightning strike, there are still some options to decrease the risk of being struck by lightning. Avoid metal objects such as motorcycles, bicycles, tractors, fences, and any objects that are taller than you. Avoid areas near pipelines, power lines, fences, ski lifts, and other structural steel fabrications. Drop metal objects such as ski poles, golf clubs, or anything that substantially increases your height. Do not waste time throwing off metal objects on your body such as jewelry, because it is a myth that wearing metal attracts lightning.

If you are unable to find a safe location, do not stand near tall, isolated trees, on hilltops, or at a lookout or other exposed areas. In a forest, seek a low area under a thick growth of saplings or small trees. Seeking a clearing to avoid large trees makes a person the tallest object in the clearing and more likely to be struck. Caves of substantial size, ditches, and valleys might provide some protection unless they are saturated with water, which can conduct current. Sheltering under a small outcropping or overhang might increase the risk of injury as rainwater pouring over the edge can drip onto you and directly connect you the path of current or splash.

If you are stuck in the open, stay away from single trees. Assuming the "lightning position" minimizes a person's height, the area touching the ground and the possibility of ground current effect. The lightning position requires squatting with both feet together and the ears covered by the hands to avoid acoustic trauma. Because this position is difficult for those of advancing age and is difficult to maintain for more than a few minutes, it seems reasonable that it would be acceptable to kneel on the ground or sit cross-legged. These positions are easier to achieve and maintain and increase ground contact only slightly [10]. Assuming this position on top of a rubber ground pad can also be of use.

If indoors during a thunderstorm, avoid open doors and windows, fireplaces, bathtubs, showers, and metal objects such as sinks, radiators, and plug-in electrical appliances. Avoid using telephones, radios, or computers. Clotheslines poles and fences can act as lightning rods. Turn off all faucets, electrical appliances, and devices before the storm, not during it.

If you are on the water, seek shore. Avoid swimming and boating or being the tallest object near a large, open body of water. Lightning will usually

strike the metal mast or other objects projecting above the water and flows well through the water to injure swimmers on the same principle as ground current injuries. Moving under a bridge or cliff while in the boat might afford some protection. Sailboats and powerboats should be protected with lightning rods and grounding equipment attached to a metal keel or understructure of the boat [73–75].

Summary

Lightning is persistently one of the leading causes of death caused by environmental or natural disaster. To understand the pathophysiology and treatment of lightning injuries one must first discount the innumerable myths, superstitions, and misconceptions surrounding lightning. The fundamental difference between high-voltage electrical injury and lightning is the duration of exposure to current. Reverse triage should be instituted in lightning strike victims because victims in cardiopulmonary arrest might gain the greatest benefit from resuscitation efforts, although there is no good evidence suggesting that lightning strike victims might benefit from longer than usual resuscitation times. Many of the injuries suffered by lightning strike victims are unique to lightning, and long-term sequelae should be anticipated and addressed in the lightning victim.

Links

http://www.nws.noaa.gov. NWS/NOAA homepage.

http://www.lightningsafety.com. National Lightning Safety Institute (NLSI) homepage.

http://www.lightning.org. Lightning Protection Institute (LPI) homepage.

http://www.uic.edu/labs/lightninginjury. Lightning Injury Research Program at University of Illinois, Chicago, Department of Emergency Medicine.

http://www.lightningstrike.org. Lightning Strike and Electric Shock Survivors International (LSESSI) homepage.

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